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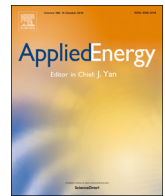
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Techno-economic analysis of the thermal energy saving options for high-voltage direct current interconnectors

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HIGHLIGHTS

- High-voltage direct current interconnectors are used for long-distance electricity transfer.
- They transfer 100 s GW of electrical power with around 1% losses mainly to heat.
- This paper compares alternative solutions for heat recovery and reutilisation.
- Data from the Moyle interconnector between Scotland and Northern Ireland is used.
- Heat-to-electricity and heat-to-cooling technologies are compared.

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ABSTRACT

High-voltage direct current interconnection stations are increasingly used for long-distance electricity transport worldwide, due to efficiency and economic reasons. The identification and evaluation of cost-effective waste heat sources appropriate for recovery and reutilisation represent an opportunity that can improve the efficiency of high-voltage direct current stations, resulting in significant savings in energy consumption and reduction of the carbon footprint. The paper is the first to investigate the technological and economic feasibility of heat recovery at a major interconnector power station. Once identified the potential recoverable heat sources and evaluated the latest advancements in thermal energy recovery technology, a technological and economic analysis of two potential heat recovery strategies has been performed. While the heat-to-electricity technology was proved to be technologically but not economically feasible, the realisation of a combined liquid desiccant and evaporative cooling heat recovery strategy was proved to present the best economic performance with a payback period of about 5 years and a levelised cost of saved energy of 0.155 €/kWh, depending on the heat recovery and size of the system. Additional economic savings can be obtained for high-voltage direct current stations located in hot and humid climates, where the moisture removal ability of liquid desiccant technology could be particularly advantageous.

1. Introduction

High-voltage direct current (HVDC) transmission lines are increasingly used all over the world for the efficient transportation of electric power over long distances. HVDC interconnector stations represent a specialized type of substation which forms the terminal equipment for an HVDC transmission line. They are used for the conversion of electricity from AC (alternating current) to DC (direct current) at the transmitting end, and back again from DC to AC at the receiving end,

based on the use of the thyristor valves [1]. The reason behind the utilisation of DC current for the long-distance transport of electricity is to be found in the lower cost and electrical losses compared to AC current. Whereas, the transport over shorter distances in underground or submarine cables are more advantageous from an economic viewpoint [1]. Additional benefits of HVDC systems are improved power flow control, and other added benefits related to stability and electrical power quality [2].

In recent years, the utilisation of interconnector power stations has

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Table 1
Overview of the currently working worldwide HVDC interconnector power stations [4,5].

	Power Installed (MW)	Power Under Construction (MW)	Power Planned (MW)	Total (MW)
Africa	2780	–	–	2780
Asia	123,568	34,800	37,000	195,368
Europe	22,498	15,240	10,800	48,538
North America	16,736	1400	12,050	30,186
South America	13,400	–	–	13,400
Oceania	2315	–	–	2315
Total	181,927	51,440	59,850	293,217

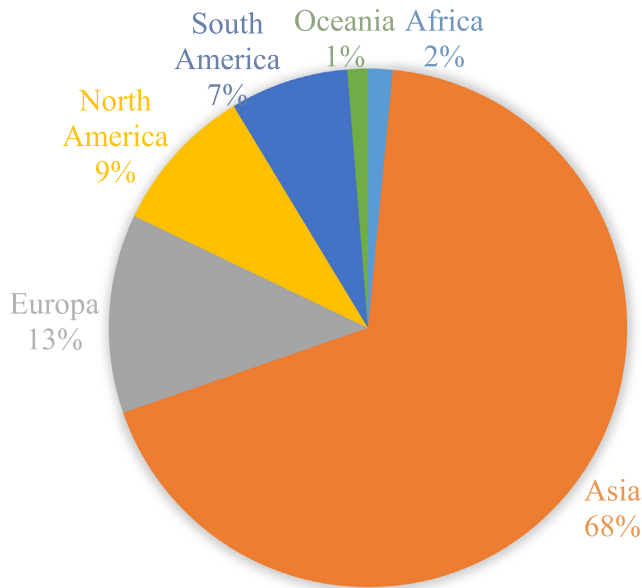


Fig. 1. Overview of the HVDC interconnector stations worldwide, . adapted from [4]

been increased to foster the flexibility and security of the electrical energy supply networks, enabling a more efficient integration with renewable energies [3]. A large number of HVDC converter station are used to transmit an increasing amount of electrical power all over the world. Table 1 and Fig. 1 give an overview of the current and planned

Table 2
List of HVDC projects in the UK, . adapted from [4]

HVDC Station	Connection 1	Connection 2	Power (kW)	Type	Year
Interconnexion France Angleterre	France – Les Mandarins	UK – Sellindge	2000	TV	1986
Moyle	UK-Auchencrosh	UK - Ballycannon More, N. Ireland	500	TV	2001
BritNed	UK – Grain	Netherlands – Maasvlakte	1000	TV	2010
East West Interconnector	Ireland – Woodland	UK – Shotton, Wales	500	IGBT	2012
Western HVDC link	UK – Hunterston	UK – Flintshire Bridge	2200	TV	2018 ^a
Caithness Moray HVDC	UK – Splital	UK – Blackhilllock	1200	IGBT	2018 ^a
ElecLink	France – Les Mandarins	UK – Sellindge	1000	n/s	2019 ^a
Nemo Link	Belgium – Bruges	UK – Richborough Energy Park	1000	IGBT	2019 ^a
IFA2	France – Tourbe, Normandie	UK – Pilling, Hampshire	1000	IGBT	2020 ^b
FAB Link	France – Cherbourg Peninsula	UK – Exeter via Alderney	1000/1400	n/s	2021 ^b
Shetland HVDC Connection	UK – Upper Kergord	UK – near Staxigoe	550/600	TV	2021 ^b
Western Isles HVDC	UK – Arnish Point, Stornoway	UK – Beaulay	600	n/s	2021 ^b
NorthConnect	Norway – Simadalen	UK – Peterhead	1400	n/s	2022 ^b
Viking Link	Denmark – Revsing	UK – Bicker Fen	1000/1400	n/s	2022 ^b
Eastern HVDC Link	UK – Peterhead	UK – Hawthorn	2000	n/s	2024 ^b

TV = Thyristor valve, IGBT = Insulated-gate bipolar transistor, n/s = not specified.

^a Under construction.

^b Planned

worldwide situation of HVDC interconnector power stations [4,5]. The European Commission recently decreed a target level of electricity interconnections equivalent to at least 10% of the domestic installed production for member countries of the European Union [6]. To further illustrate this, Table 2 lists the HVDC projects currently working, under construction or planned in the UK alone [4]. As shown, an always growing number of HVDC stations characterised by bigger power size is currently under construction or planned for the next few years.

The table shows how two main HVDC technologies are used in the UK and worldwide: thyristor- and insulated-gate bipolar transistor-based (IGBT) technology. While thyristor-based systems are the conventional choice for long-distance electricity transmission, IGBT-based systems are getting more interest in the recent period due to their ability to control turn-off capability [7]. Whilst the IGBT technology presents different energy losses respect thyristor-based, its higher conduction losses makes likewise the technology appealing for heat recovery projects. However, the paper will only focus on thyristor-based systems.

Furthermore, a new interest for efficient long distance, bulk power transmissions for a higher integration of renewable energy sources as hydroelectric, has led to the development of the what so-called ultra-high-voltage direct current (UHVDC) converter station (800–1000 kV). Examples of long-distance transmission of energy are present in China, India, Africa, Amazon, etc. [8]. An always growing number of UHVDC will be built in the future to connect on energy sources and demand on a larger scale.

With the increasing number of HVDC converter stations worldwide, the potential impact associated with incremental efficiency improvements in the MW scale is significant. The majority of these losses are in the electricity AC/DC conversion process, with significant heat losses involved. As a result, identifying opportunities to recover waste heat from HVDC converter stations has significant potential to reduce primary energy sources and greenhouse gas emissions.

In recent years, environmental issues and energy saving concerns have led to intensive research activities around energy-efficiency and low-grade heat recovery technologies [9,10]. Given the increase of global energy consumption, the increasing cost of electricity and fossil fuel resources, and the future scarcity of the latter, the identification of alternative and sustainable technologies able to ensure the same level of comfort, while reducing the primary energy consumption remains a top priority. Moreover, a reduction in electricity consumption obtained through heat recovery can positively affect GHG emissions. As reported by [11], the heat currently released in the UK is estimated to be around 11.4 TWh/y. However, most of the heat released by industrial

processes, data centers, etc. is low-grade with a temperature lower than 200 °C [12]. This is analogous to the case of HVDC interconnector sites, where the reported temperatures of the waste heat produced by the components most responsible for heat losses, transformers and thyristor valves, is lower than 100 °C. The recovery of waste heat in this temperature range is often economically unfeasible and must be carefully evaluated. The identification and evaluation of technologies able to economically recover and utilise the waste heat present at a power interconnector site is the core aim of this paper.

The novelty of this work is that it represents the first detailed evaluation of potential technologies for the recovery of low-grade waste heat from the power conversion equipment of HVDC interconnectors. This evaluation will be underpinned by technical performance data provided by the Moyle interconnector substation, transmitting power between Scotland and Northern Ireland. Technological and economic assessment of the feasibility of the recovery and use of the waste heat produced by thyristors valves and transformers is carried out. Between the different active heat recovery technologies, two strategies are considered in the paper: technologies for waste heat utilisation to produce cooling and dehumidification (liquid desiccant and solid desiccant systems coupled with evaporative cooling), and technologies for electricity production, based on a combination of waste heat upgrading technology, e.g. absorption heat transformers (AHT), and conversion of waste heat in electricity, e.g. Organic Rankine Cycle (ORC) systems. Therefore, the paper is structured as follows: Section 2 defines the scope of the paper and the methodology used for the technological and economic analysis, investigating the possible heat recovery technologies and classifying the different technologies in thermally-driven air-conditioning technologies (liquid desiccant, solid desiccant, and evaporative cooling) and power generation (combination of heat upgrade with AHT and electricity production with ORC). Section 3 identifies the heat sources present at the Moyle HVDC interconnector site, particularly describing the thyristor valves and transformer and the unexploited heat currently wasted. Section 4 evaluates the technological performance of the identified heat recovery strategies. In Section 5, the technological challenges for the retrofitting on the Moyle interconnection site are described and two different heat recovery strategies (using air or water as heat transfer medium) are identified. To conclude with, the economic analysis of the two identified heat recovery strategies is performed (Section 6).

2. Scope and methodology

The paper aims to evaluate from a technological and economic point of view the potential heat recovery strategies possible at HVDC converter stations. Given the scale of the power transmitted through HVDC stations and the significant heat losses present, the implementation of heat recovery would result in significant economic benefits for HVDC manufacturers. The methodology used in the study is shown in Fig. 2.

2.1. Literature review of heat recovery options

A detailed analysis of the major technologies for waste heat recovery and utilisation was conducted, including power generation technologies (ORC, Kalina cycle and thermoelectric power generation), heating technologies (direct space heating, district heating, heat pump), heat-to-cooling technologies (absorption cooling, adsorption cooling, desiccant evaporative cooling, ejector cooling), and some thermal upgrade technologies (such as solar thermal booster and absorption heat transformer).

The range of economically viable potential recovery technologies is limited by their low operational temperatures. Through an evaluation of the Moyle interconnector site's landscape and of the possible domestic or local application of the heat recovery, only cooling and power generation technologies were considered favourable in the current study, given the very little heat demand at the station or around. A

summary of the advantages and drawbacks of the identified heat recovery strategies is displayed in Table 3. The potential heat recovery strategies are further described in the next paragraphs.

2.1.1. Humidity removal and cooling by desiccant technology

Desiccants are substances characterized by their hygroscopic property, namely their affinity to water molecules. These substances are able to efficiently dehumidify the air, sorbing the water molecules present in it. Depending on their physical state, desiccants can be classified in solid and liquid. The two desiccant categories differ for the physics of their water sorption process, namely absorption for liquid and adsorption for solid desiccants [13]. Their regeneration process (desorption of water molecules to a scavenging air stream) is driven by heat, obtainable by renewable energies, such as solar-thermal, geothermal, etc., or recovered by industrial processes.

2.1.1.1. Liquid desiccant and evaporative cooling system. Liquid desiccants are hygroscopic solutions characterised by a low equilibrium vapour pressure, able to absorb water molecules from the outdoor air. Different typologies of solution can be employed as desiccant, such as halide salt solutions (LiCl, LiBr, CaCl₂, etc.), triethylene glycol (TEG), potassium formate (HCO₂K), and ionic liquids. Each of these desiccant solutions presents different thermodynamic properties and cost. The choice of the desiccant solution used is decisive for the overall performance of the system [14]. As noted above, the LDAC system is able to efficiently dehumidify the air and deal with latent loads of buildings and humidity removal applications. However, this technology is usually not able to cover sensible loads of buildings and is hence integrated with additional air-cooling systems [15,16], such as electrically-driven vapour compression chiller (hybrid system) [17], absorption chillers [18], and evaporative cooling systems [19], direct or indirect. In this study, the combination of liquid desiccant with direct evaporative cooling was considered. The schematic diagram of the system is shown in Fig. 3.

As shown in the Figure, the cold strong desiccant solution is sprayed from the top of the dehumidifier, contacting the air that is blown from the bottom. As the solution and air contact, the liquid desiccant will tend to drive off the moisture from the air stream. The driving force of the process is the low equilibrium vapour pressure of the solution respect the partial vapour pressure of water molecules in the air. The migration of water molecules from the air to desiccant solution continues until the solution reaches equilibrium with the air. In the regenerator, the opposite process happens, as the hot weak desiccant solution desorbs water to the counter-current (or cross-current) flow scavenging air, becoming again a strong solution. For the absorption/desorption process to happen, the solution must be cooled/heated before entering the dehumidifier/regenerator, respectively. The heating source can be obtained by renewable energies or waste heat recovery, while the cooling source is usually a cooling tower. The air after being dehumidified by the liquid desiccant air-conditioning system is cooled by an evaporative cooling system and then supplied to the air-conditioned zone. Depending on the temperature and humidity requirements and costs, a direct or indirect evaporative cooler can be used in combination with liquid desiccant technology. When a direct evaporative cooler is used, water evaporates into the dry air with consuming sensible heat from both water itself and dry air. Then the dry air becomes cool wet air ready to be supplied to the air-conditioned zone.

2.1.1.2. Solid desiccant and evaporative cooling system. Solid desiccants are materials able to physically adsorb water molecules that condense inside the surface of the adsorbent material, such as silica gel, zeolite, synthetic zeolites, activated alumina, carbons, synthetic polymers, CaCl₂/LiCl/LiBr composite with supporting material, etc. [20]. The desiccant material is usually embedded in a wheel configuration to ease the regeneration process [21]. Fig. 4 depicts an example of solid desiccant wheel combined with an evaporative cooling system.

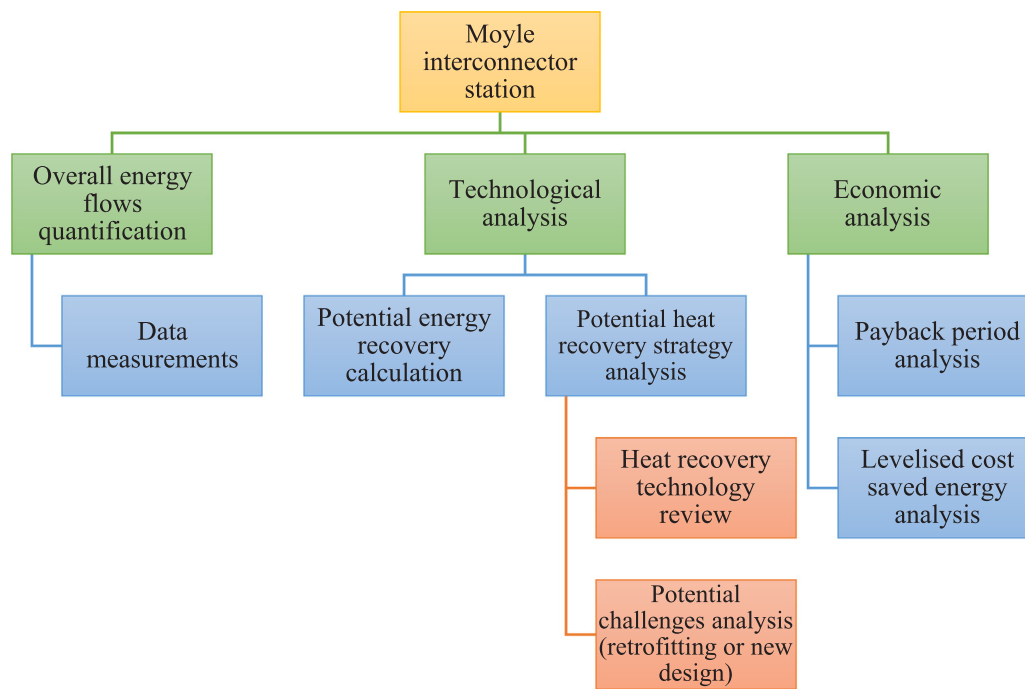


Fig. 2. Methodology used in the study.

Table 3
Benefits and drawbacks of the identified heat recovery strategies.

	Cooling	Heating	Power generation
Advantages	Cooling demand is large	Direct usage	Flexible energy form
Disadvantages	Waste heat temperature is not high	Heating demand is low	Waste heat temperature is too low; upgrade is necessary
Potential technology	Desiccant evaporative cooling	–	Absorption heat transformer and organic Rankine cycle

In the system, a desiccant rotary wheel is integrated with a heat recovery wheel and a direct evaporative cooler to reach the desired condition for the building's supply air. As the process air passes through the desiccant wheel, it releases humidity to the desiccant wheel. This ideal process performed by solid desiccant is isenthalpic, resulting in a temperature increase of the dehumidified air. As the desiccant wheel rotates, the desiccant material is heated and regenerated, desorbing the water vapour previously absorbed into the air exhausted by the room. The warm dry air produced by the desiccant wheel is then pre-cooled in a heat recovery wheel, which has also the function of pre-heating the

return air, reducing the heating consumption for the desiccant wheel regeneration. Additional cooling is provided by the evaporative cooler, where the dry air becomes cool wet air that can be delivered to the building. The return air exhausted from the room passes through another evaporative cooler first and then releases its cool energy to the warm dry air in the heat recovery exchanger.

2.1.2. Heat upgrade and power generation

Production of electricity with an organic Rankine cycle (ORC) system driven by the heat upgraded by an absorption heat transformer

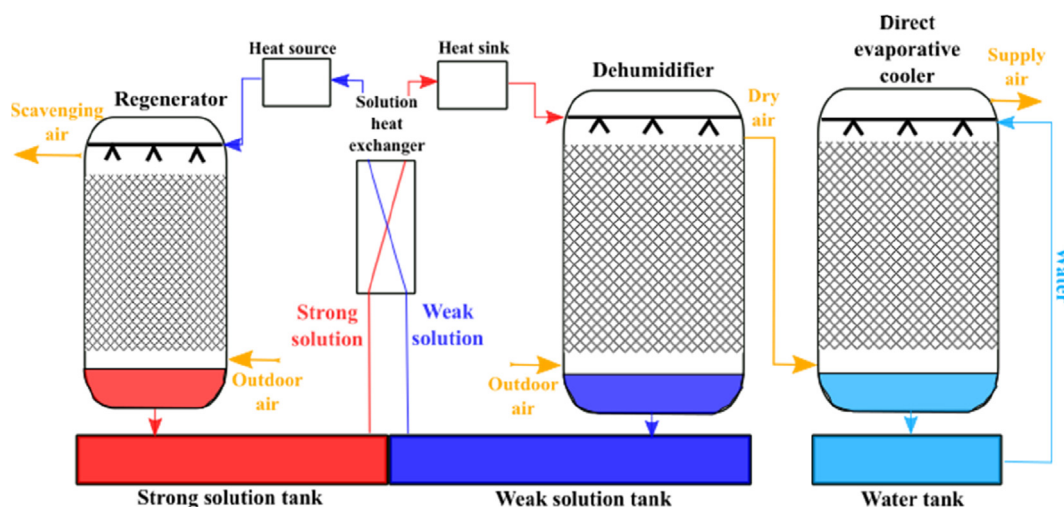


Fig. 3. Schematic diagram of a combined liquid desiccant and direct evaporative cooling system.

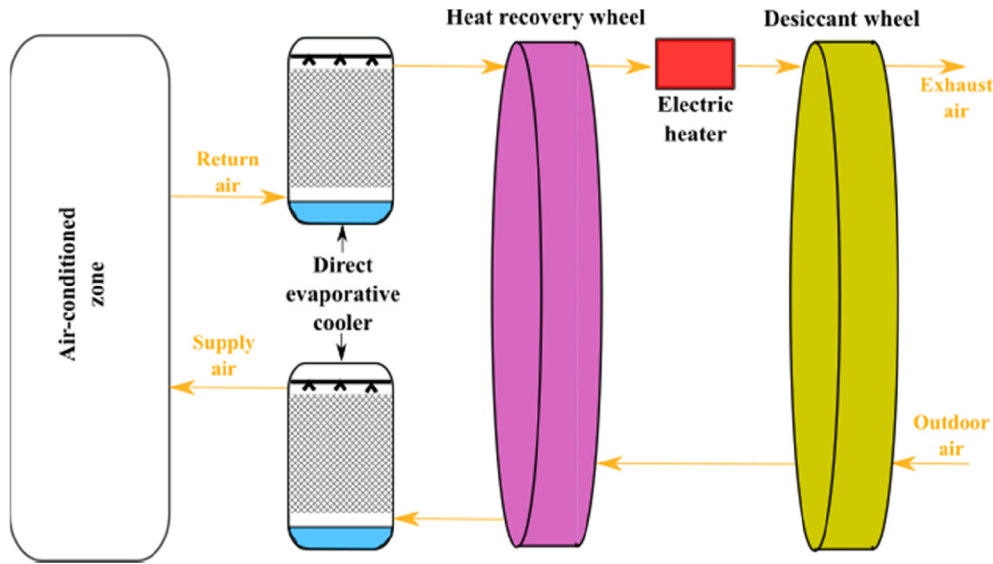


Fig. 4. Schematic diagram of a combined rotary wheel solid desiccant dryer and direct evaporative cooling system.

(AHT) is the second identified heat recovery strategy at Moyle interconnector. The main components are further described.

2.1.2.1. Absorption heat transformer. AHT technology is used to boost the waste heat temperature, producing higher quality heat that would otherwise have been mostly produced with fossil-based energy sources. The AHT working principle is the reverse of an absorption chiller [22]. The general schematics of the system in single and double stage configuration is displayed in Fig. 5. The main components of the system are generator, absorber, evaporator, condenser, and solution heat exchanger.

As represented in the Figure, the low-temperature heat source (lower than 100 °C) is supplied at the same temperature to evaporator and generator, at the same time or to the evaporator first and then to the generator. In the condenser, the working fluid is condensed at ambient temperature releasing heat at low-temperature. The useful effect of the system is the heat is released in the absorber, which is at a higher temperature due to the higher pressure. As a result, the input waste heat can be upgraded to a high temperature and collected at the absorber for a more efficient utilisation [23]. Different working fluids have been used in AHTs, such as LiBr-H₂O, NH₃-H₂O, and H₂O-Carrol (a mixture of LiBr-Ethylene Glycol in ratio 1:4–5 wt) [24]. The employment of different working fluids strongly influences the overall performance of the system and therefore must be carefully evaluated. For the determination of the thermal performance of an AHT, the coefficient of performance *COP* is used and defined as [25]:

$$COP = \frac{Q_{abs}}{Q_{evap} + Q_{cond}} \quad (1)$$

where Q_{abs} , Q_{evap} , and Q_{cond} represent the heat released or absorbed by the absorber, evaporator, and condenser, respectively. The temperature lift ΔT achievable by the AHT at the absorber is defined as [26]:

$$\Delta T = T_{abs} - T_{evap} \quad (2)$$

where T_{abs} and T_{evap} represent the temperature at the absorber and evaporator, respectively. Common values for the temperature lift that can be obtained with a single-stage AHT are around 30–40 °C [25]. This feature of single-stage AHT limits the employment of the technology. A significant increase in the temperature lift can be reached using a double-stage AHT [25].

2.1.2.2. Organic Rankine Cycle. Organic Rankine Cycle (ORC) is a heat conversion technology able to convert low-temperature heat into electricity. These systems use organic fluids as working fluid of the system. These fluids are characterised by a lower boiling point respect steam, increasing the useful work of the system (electricity production) when dealing with low-temperature heat [27]. The use of different working fluids strongly influences the performance and economics of the system [28]. The configuration of a typical ORC system is illustrated in Fig. 6.

The working principle of ORC is the same of the Rankine cycle. The working fluid is pumped to a boiler where it is evaporated as it passes

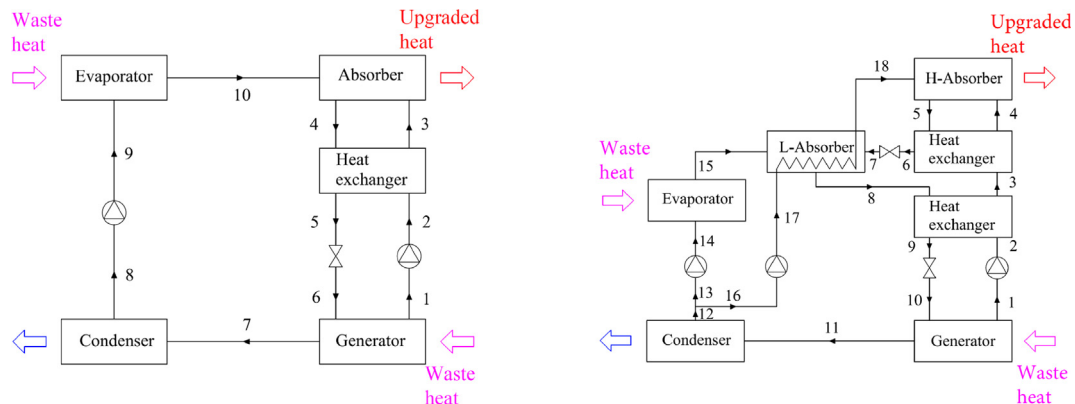


Fig. 5. Schematic diagram of single stage (left) and double stage (right) absorption heat transformer.

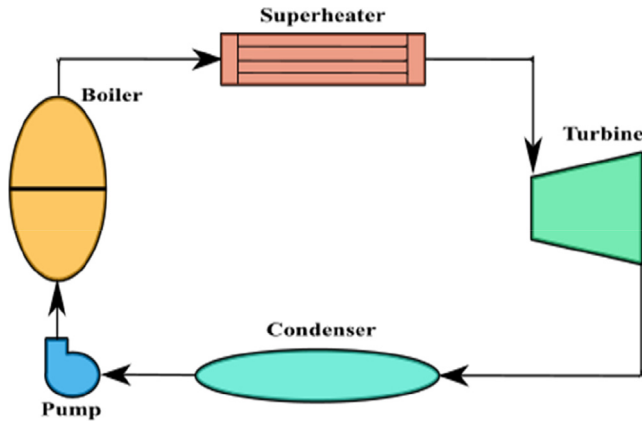


Fig. 6. Schematic diagram of ORC system.

through an expansion device (turbine or other expanders), generating power. The working fluid at the outlet of the expansion device passes through a condenser heat exchanger where it is finally re-condensed. The liquid working fluid is again pressurized by the pump, closing the ORC cycle [29]. Respect the Rankine cycle, the lower working temperature of an ORC makes this technology particularly interesting for the conversion of low-temperature waste heat into electricity.

Today's energy-saving concerns have facilitated the development of ORC technology for employment of low-temperature heat sources, such as renewable energy (solar energy, geothermal heat, biomass, etc.) or recovered by industrial waste heat, to produce electricity [30]. The heat recovery strategy based on the combination of AHT and ORC is of recent interest [31].

2.2. Economic analysis

The cost-effectiveness of the technology replacement for the low-grade heat recovery was evaluated using two different metrics: the *payback period* and the *levelised cost of saved electricity*. The *payback period* represents a simple comparison between capital and operational costs of the conventional and replacement technology and to identify the economic return on the investment and is defined as:

$$\text{Payback period} = \frac{\text{CAPEX}_{\text{repl}} - \text{CAPEX}_{\text{conv}}}{\text{OPEX}_{\text{conv}} - \text{OPEX}_{\text{repl}}} \quad (3)$$

where $\text{CAPEX}_{\text{repl}}$ and $\text{CAPEX}_{\text{conv}}$, and $\text{OPEX}_{\text{repl}}$ and $\text{OPEX}_{\text{conv}}$ represent the capital and operational cost of the replacement and conventional technology, respectively. Whereas the *levelised cost of saved electricity* (LCOSE), indicates the cost for saving each kilowatt hour of electric energy by replacing the conventional system over the lifespan of the machine. The LCOS is defined as [32]:

$$\text{LCOSE} = \frac{\text{Investment}}{\text{Electricity saved}} = \frac{\text{CAPEX}_{\text{repl}} - \text{CAPEX}_{\text{conv}} + \sum_{k=1}^n \left[\frac{\text{OPEX}_{\text{repl}}}{(1+i)^k} \right]}{\sum_{k=1}^n \left[\frac{\text{Elec}_{\text{conv}} - \text{Elec}_{\text{repl}}}{(1+i)^k} \right]} \quad (4)$$

The parameter evaluates the economic viability of the technology replacement over the lifespan of the machine, assumed as 20 years. $\text{Elec}_{\text{conv}}$ and $\text{Elec}_{\text{repl}}$ represent the electricity consumed in kWh by conventional and replacement technology. The discount rate i is assumed as 3% [32].

3. Moyle interconnector station and waste heat sources identification

3.1. Moyle interconnector station

Went into service in 2001, the HVDC Moyle interconnector links the electricity grid between Auchencrosh, Scotland, and Ballycran More, Northern Ireland. Its geographic location and schematic diagram are displayed in Fig. 7 [33]. This interconnection station consists of two monopolar 1000 A 250 kV DC cables each with a transmission capacity of 250 MW. The characteristics of the system are summarised in Table 3.

The first step of the study was the evaluation and quantification of available heat sources on-site. Based on the analysis of converter stations like Moyle, the converter would be expected to lose around 1% of the total transmission power during the AC/DC conversion process (or vice versa) [34]. This would equate to approximately 5 MW of the total transmission energy being lost to the ambient environment via heat transfer. Fig. 8 shows the distribution of heat losses in the different components of an HVDC station [35].

The components whose heat recovery has been considered feasible are transformers (~50% of the total losses) and thyristor valves (~30%). These two components are further described in the following paragraphs.

3.2. Thyristor valves

The thyristor valve is a basic component of the modern HVDC converter used for the conversion of AC current to DC. The operation of the thyristor releases heat, which should be extracted under controlled conditions to achieve adequately low temperature rise across these components. In Moyle, the removal of heat produced by thyristor valves is currently performed by a combination of liquid cooling with pure deionised water and air ventilation system. An example of thyristor valves hall and related ventilation air system is displayed in Fig. 9. The inlet air enters through the fan coil unit located on the side of the thyristor valves' stack, while the hot ventilation air heated after passing through the valves' stack is expelled through outlet doors on the ceiling. The high voltage in the proximity of the thyristor valve stack puts a

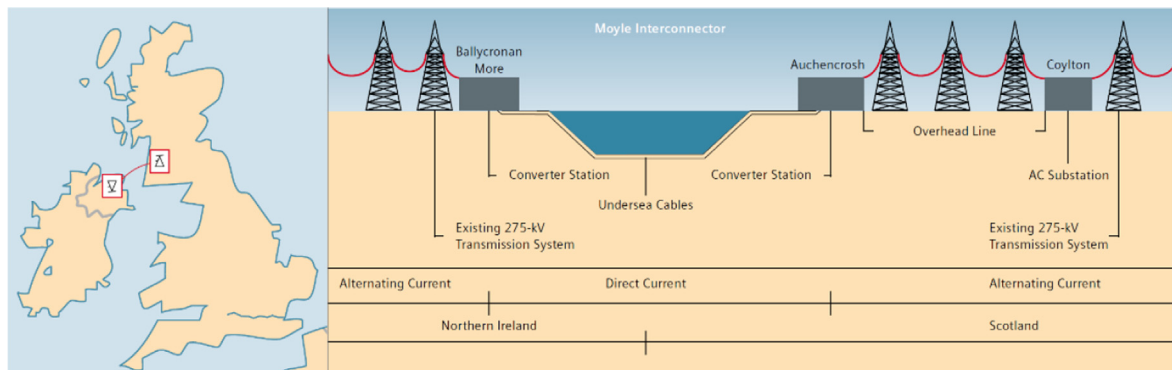


Fig. 7. Schematic diagram of Scotland – Northern Ireland HVDC station [33].

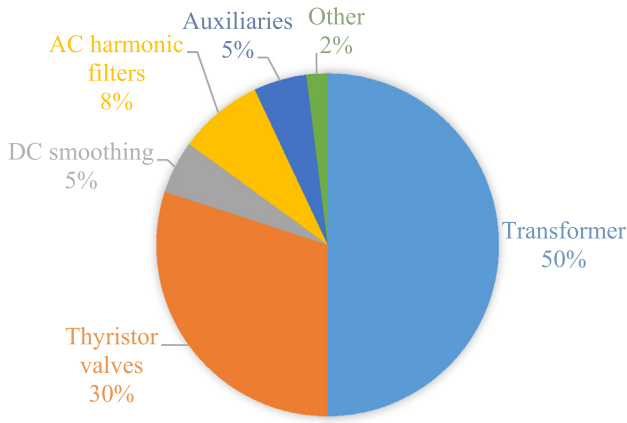


Fig. 8. Evaluation of the heat losses per component of a HVDC station [35].

limitation on the placement of conductive materials in the hall, restraining the positioning of the air inlet ports [36].

The deionised water cooling system for the thyristor valves used in Moyle is shown in Fig. 10. Given the use with high voltage equipment, the installation is safe if the water is ultra-pure, ensuring that no ionic contaminants are present to limit its conductivity [36]. As displayed in the Figure, the water coolant is distributed in parallel to every thyristor level in the valve via thin plastic pipes and is pumped to and cooled through an air-water heat exchanger. To maintain the thyristor valves' temperature at around 40 °C, the water supplied to the thyristor is at the temperature range of 35–40 °C with an outlet of 40–45 °C. The volumetric flow rate of the water is set at 100 m³/h. The available waste heat from the thyristors can be calculated according to the heat balance:

$$Q = \dot{m}c_p\Delta T \quad (5)$$

where \dot{m} is the mass flow rate of water, c_p is the specific heat of water, and ΔT is the temperature difference between inlet and outlet water in the thyristor valves stack.

To design a good air ventilation system of thyristor valves hall and ensure proper and continuous operation of the system, the supply air must meet specific requirements in terms of temperature, humidity and dust content. Overheating and water condensation on the thyristor valves must strictly be avoided. Two vapour-compression refrigerators (74 kW each) are currently used in the system to control the

temperature and the humidity of the air inside the thyristor hall, which is set at 15 °C all through the year. The failure in providing the adequate values of temperature and humidity in the hall may result in malfunction of the thyristor valves, potentially causing the shutdown of the system [37]. Moreover, a too humid environment in the thyristor valves hall results in an increased potential of corona discharge [38]. This phenomenon of electrical discharge caused by a high electric field strength surrounding a conductor material has a negative effect on the operation of the HVDC converter, causing higher losses. Dust is also responsible for an increase of corona discharge [39]. Additional drawbacks resulting by a too humid environment in the HVDC hall is the potential rusting in valves and controls [40]. Values of temperature and humidity in thyristor valves hall have been recommended by IEC standards [39]. Maximum allowable values are 40 °C for the air temperature and 60% for the relative humidity. In addition, moisture coming from leaks in the walls or via poorly fitted doors or water released by wet or flooded cables are potential internal moisture sources in substations that must be also be accounted to ensure proper working of the components [39].

3.3. Transformers

Transformers are used for the conversion of energy from one voltage level to another. During this conversion process, losses occur as heat, which must be dissipated by a cooling system. Depending on the cooling type of the transformer, this can be classified in: Oil Natural Air Natural Type (ONAN), Oil Natural Air Forced Type (ONAF), Oil Forced Air Natural Type (OFAN), and Oil Forced Air Forced Type (OFAF) [41]. The transformer used in the Moyle interconnection station is of the OFAF type, which cooling system schematic is shown in Fig. 11. The heat produced by the transformer is dissipated by the oil circulating between the transformer and radiator. In the radiator, the heat content of the oil is reduced with the aid of a fan which blows air from below.

The characteristic and limits of an OFAF transformer are expressed in Table 4. For OFAF transformers, the oil temperature at the top of the radiator must be maintained at under 105 °C for normal life expectancy loading, while its temperature is usually ranging between 55 and 85 °C during practical operation [42] (see Table 5.).

The heat recovery from large power transformers is a technology that has been already investigated in the past [43,44]. The energy loss in the transformer can be calculated as:

$$E_{loss} = (P_0 + P_k * I^2) * t \quad (6)$$

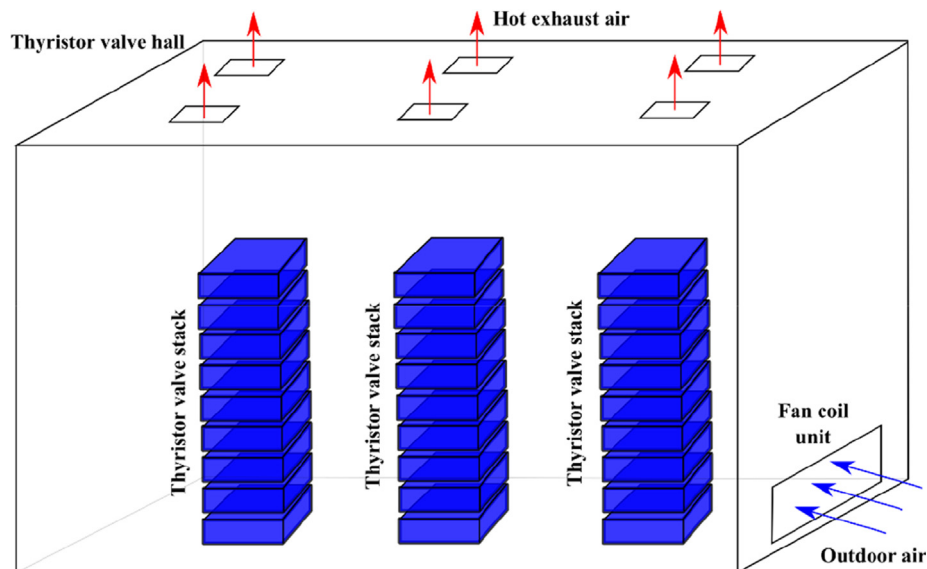


Fig. 9. Ventilation air system of thyristor valves hall.

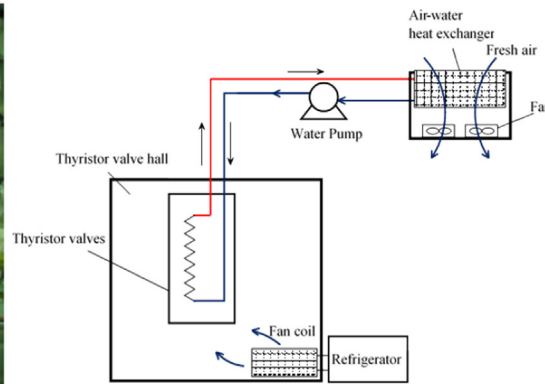
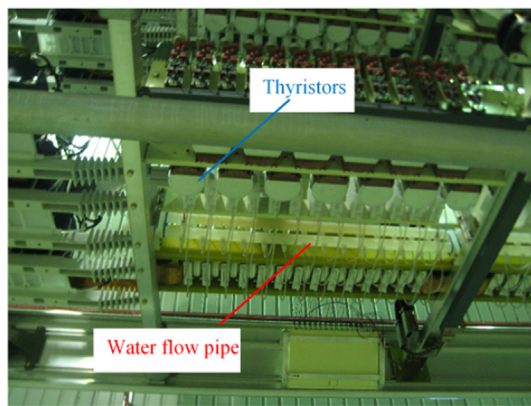


Fig. 10. Cooling system for the thyristor valves hall in Moyle.

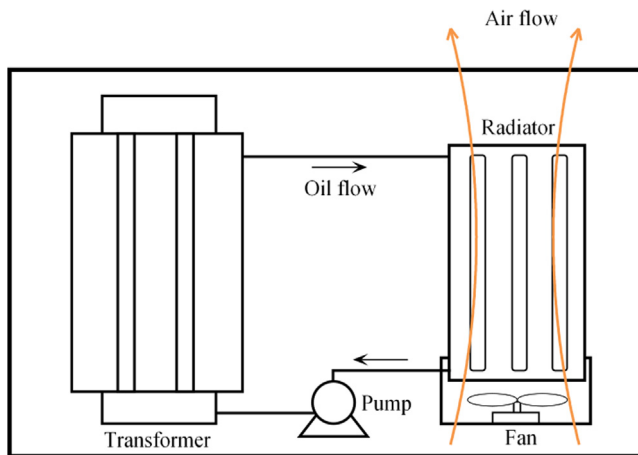


Fig. 11. Schematic diagram of OFAF transformer.

Table 4
Characteristics of the Moyle interconnector site.

Characteristic	Quantity
Transmission capacity (MW)	250 ^a
System voltages (kV)	Direct current: 250 Alternate current: 275
Rated current (A)	1000
Transmission distance (km)	63.5

^a 2 poles at each site.

where P_O is the no-load loss (kW), P_k is the load loss (kW), I is the rms-average load of the transformer, t is the annual working hours.

3.4. Data collection and waste heat calculation

3.4.1. Thyristor valves hall

To evaluate and calculate the heat potential present on site, operational data for the interconnecting substation of Moyle from years 2009 and 2014 were provided by the company Mutual Energy, operator

Table 5
Characteristic and limits of OFAF transformer [41].

	Normal life expectancy loading	Planned loading beyond nameplate rating	Long-term emergency loading	Short-term emergency loading
Top-oil temperature (°C)	105	110	110	110
Hot-spot temperature (°C)	110	130	140	180
Loss-of-life factor	1.0000	6.9842	17.1994	424.9218
Resulting life (hours)	65,000	9307	3779	153

of the station. The provided data are shown and summarised in Fig. 12 and Table 6 together with the calculated waste heat power. Over the considered period, there was increasing energy market modernisation and roll-out of renewable energy across both Ireland, Northern Ireland and Scotland. As such, the direction of energy flow as well as the load saw greater variance. Furthermore, there were periods in which the components of the system were repaired and the whole system was not operated.

The table shows how the available waste heat at 39.0–43.4 °C in pole 1 (operating all the year) is on average 385 kW. Pole 2 was operated intermittently with an average power of 385 kW when operated but only 268 kW when considering the whole year timespan. In the condition when both the poles were operated as in 2009, the available waste heat reaches 770 kW. The analysis of the year 2014 shows lower values of available waste heat. This is because the Pole 1 was operated all over the year except July and August, while Pole 2 was not operated.

3.4.2. Transformer

For the transformer waste heat evaluation, data on the oil temperature and flow rate were required. However, these parameters were not routinely monitored or measured in the Moyle interconnection station. This lack of data was overcome by considering data reported on literature [42–45]. Table 7 shows the efficiencies and losses of different transformer types [45].

As reported in the Table, the efficiency of an interbus scale transformer (rated power at 400 MVA) is 99.75% at 50% rated load, and all the losses are in the form of heat [45]. For this reason, a value of 0.25% of the heat content has been used for the calculation of the available waste heat in the transformer. Table 8 displays the calculated recoverable waste heat from the transformer.

The table shows that about 678 kW of waste heat can be recovered under the condition when both the poles were operated, such as in 2009. The temperature of the oil ranges between 55 and 85 °C, particularly relevant for low-temperature heat recovery.

4. Technological analysis of heat recovery options

Once identified and quantified the waste heat sources at the Moyle interconnector station, an analysis of the performance of potential heat

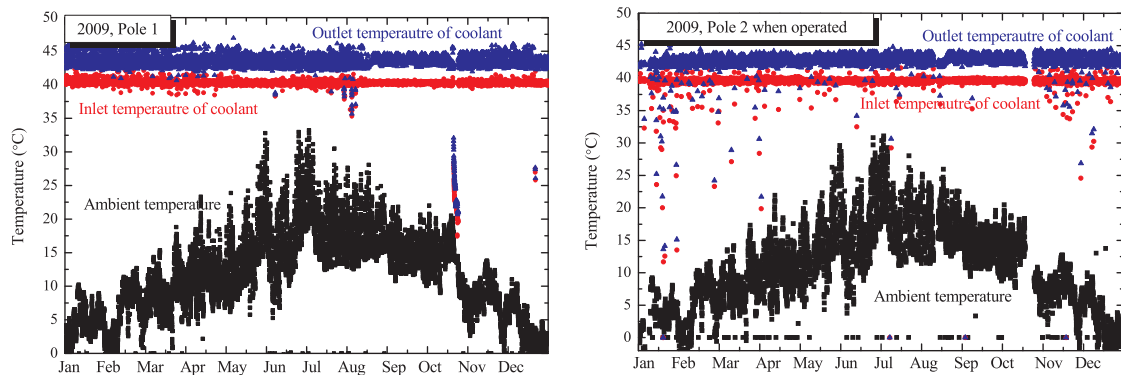


Fig. 12. Ambient air, inlet and outlet cooling water temperature for Pole 1 and Pole 2 in 2009.

Table 6

Measured data and calculated waste heat from the thyristor valves cooling system.

	2009 Pole 1	2009 Pole 2	2014 Pole 1
Ambient temperature (°C)	−3.6 ~ 33.2; Average: 11.6	−3.4 ~ 32.3; Average: 12.1	−1.1 ~ 34.8; Average: 10.9
Coolant inlet temperature (°C)	Average: 40.1	Average: 39.5 Max: 41.8	Average: 40.3 Max: 42.5
Coolant outlet temperature (°C)	Average: 43.4	Average: 42.8 Max: 45.9	Average: 44.1 Max: 47.1
Temperature difference (°C)	2 ~ 5.6 Average: 3.33	0 ~ 5.4 Average: 3.3	1.4 ~ 5.7 Average: 3.8
Power (MW)	−80 ~ 250 Average: 120	14 ~ 242 Average: 151	−245 ~ 250 Average: 146
Average waste heat (kW)	385	385 (268 whole year)	443 ^a

^a Temperature sensor failed in October.

recovery strategies was conducted.

4.1. Performance of hybrid desiccant and evaporative cooling system

To evaluate which strategy for humidity removal and cooling could better perform at Moyle interconnector, advantages and drawbacks of the technologies were discussed:

- Both technologies are able to remove moisture from the air more efficiently than electrically-driven vapour compression system, where humidity is removed by cooling the air to the dew-point, overcooling of the air below dew-point and moisture removal for condensation, and reheating to the required conditions of air for the building. This process is highly inefficient from an energetic point of view and results costly for applications where humidity control is performed, as in thyristor valves hall where it is kept under control to avoid condensation on the valves and limit corona discharge. Fig. 13 compares the two processes on a psychrometric chart. The figure was obtained considering as outdoor air condition the average temperature and humidity at Moyle in July 2018 ($T = 13.9^\circ\text{C}$, $\text{RH} = 82\%$).

Table 7

Efficiencies and losses of transformers in different scales [45].

Transformer type	Rated Power (MVA)	Efficiency (%) at		Loss (kW) at	
		100% Rated Load	50% Rated Load	100% Rated Load	50% Rated Load
Generator transformer	1100	99.60	99.75	4400	1375
Interbus transformer	400	99.60	99.75	1600	500
Substation transformer	40	99.40	99.60	240	80
Distribution transformer	1	98.60	99.00	14	5

Table 8

Waste heat from the transformer. Calculation based on 0.25% heat generation.

	2009 Pole 1	2009 Pole 2	2014 Pole 1
Power (MW)	−80 ~ 205 Average: 120	14 ~ 242 Average: 151 (108 whole year)	−245 ~ 250 Average: 146 (120 whole year)
Waste heat (kW)	300	378 (270 whole year)	365 ^a
Temperature (°C)		55–85 °C ^b	

^a Temperature sensor failed in October.

^b Valid for all the conditions.

The air dehumidification process with solid desiccant results in producing overheated dry air, which must be cooled before supplying it to the conditioned air zone. Under proper operation, liquid desiccant air-conditioning systems are able to simultaneously dehumidify and cool the air [16]. From an energetic point of view, liquid desiccant is hence the best choice for humidity control.

- The temperature required by the liquid desiccant regeneration process is lower than solid desiccant. Depending on ambient outdoor air conditions and desiccant solution, liquid desiccants require a regeneration temperature in the range 40–70 °C, while the temperature required for regeneration is in the range 60–115 °C for a solid desiccant as silica gel [46]. The waste heat present at the HVDC converter station might not be enough to drive the regeneration of a solid desiccant system.
- The structure of the solid desiccant systems is simpler, but their ability to hold moisture is lower [46]. The materials used as solid desiccant are cheaper than liquid desiccant solutions [47].
- Any possible entrainment of liquid desiccant droplets in the air supplied to the building must be strictly avoided for health and safety reasons [48]. Carryover of the desiccant solution is one of the main drawbacks of LDAC systems. Common desiccant systems employ a demister after the dehumidifier to stop any possible entrainment of liquid desiccant droplets in the air supplied to the conditioned zone. This technological solution results in an increase in the cost of the system and of its maintenance cost and in higher electricity consumption to blow the air through the system [48].

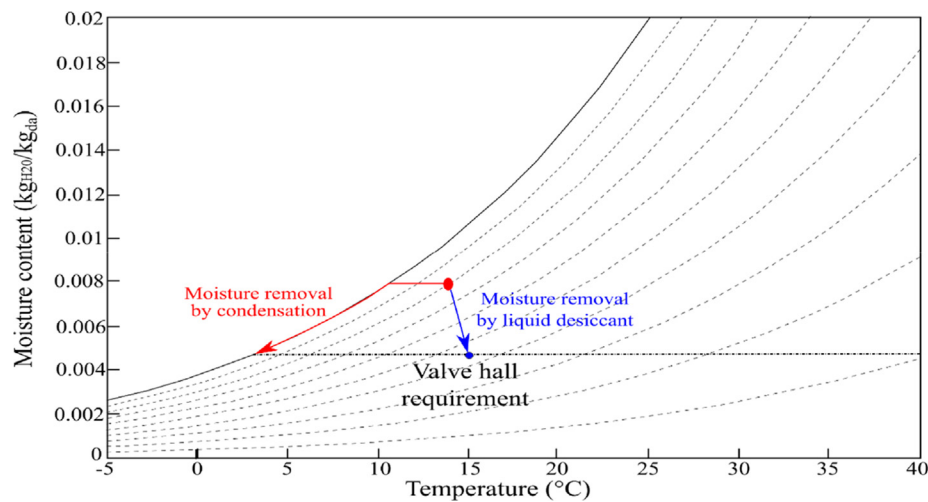


Fig. 13. Comparison of humidity removal by condensation (red line) and by liquid desiccant technology (blue line).

More recently, an alternative solution has been the development of indirect contact liquid desiccant system, involving the use of a membrane contactor between air and solution [49].

- The COP of solid desiccant systems is estimated to be around 0.4, while the COP of liquid desiccant air-conditioning systems can reach a value of approximately 0.8 [50]. As reported by [51], the COP of the liquid desiccant air conditioning system can be slightly increased by reducing the parasitic losses.
- Unlike solid desiccant technology, liquid desiccant technology offers the opportunity to store the waste heat in thermo-chemical form. This thermo-chemical energy can be stored almost free-losses and exploited when cooling is needed [52].
- Given the open-system characteristic of liquid desiccant systems, dehumidification and regenerator of the system can be split [53]. The flexibility of liquid desiccant allows locating the regenerator and the dehumidifier where the heat sources are present and where the cooling and dehumidification effect is needed, respectively [54].
- The dehumidification process with liquid desiccant technology is a “dry” process, not involving the use of fan coils, which wet surfaces are possible breeding sites of bacteria, moulds, E-coli, etc. [14]. In addition, desiccant solutions, particularly halide salt solutions such as LiCl and LiBr, are able to remove, filter, or kill bacteria and virus [55]. Particularly important for HVDC stations is the ability of liquid desiccant technology to filter dust [56] which results in increased corona discharge effect and higher electric losses and must be kept under control.

After all these considerations, the combination of liquid desiccant and evaporative cooling has been considered as the most favourable technology in the Moyle interconnection site. A first estimation of the potential cooling energy producible by this system is summarised in Table 9. The COP for combined liquid desiccant evaporative cooling technology is highly dependent on outdoor air condition [57]. The calculations are performed considering an outdoor air temperature of

10 °C and a COP for the desiccant evaporative system of 0.2 in the case of a 45 °C waste heat stream (thyristor valve coolant heat recovery), and of 0.4 in the case of transformer coolant heat recovery.

The table shows how the estimated potential cooling effect utilising desiccant evaporative cooling provided by the waste heat from thyristors in the year 2009 when both poles are operating is about 425.2 kW.

4.2. Performance of absorption heat transformer & ORC

Electricity production with combined AHT + ORC system considering a waste heat stream at 40 °C present in the Moyle interconnector site was studied. The first step of the process is the temperature lift performed by the AHT. Based on theoretical calculations, the obtainable temperature increase of water for a single stage AHT with an efficiency of 0.42 is from 40 to 70 °C. The thermodynamic behaviour of a single-effect absorption heat transformer is shown in Fig. 14.

Fig. 14 shows the temperature lift of single effect AHT considering an ambient temperature of 10 °C (black line) and 20 °C (red line) for a waste heat of 40 °C (thyristor valves heat recovery assumption) and 60 °C (transformers heat recovery assumption). The upgraded temperature obtainable with the system is between 45 °C and 70 °C in the thyristor valves’ case, while between 75 and 110 °C in the transformers’ case. This temperature is not enough for power generation with an ORC cycle. Alternatively, the increase of the waste heat temperature with a double stage AHT was investigated. The possible achievable temperature lift considering a 40 °C waste heat input, a 10 °C outdoor air condition, and an efficiency of 0.3 is 90 °C. The thermodynamic behaviour of a double effect AHT is shown in Fig. 15. The figure shows how the system shows a better performance respect the previous case, producing an upgraded temperature between 70 and 105 °C in the thyristor valves’ case, while between 100 and 170 °C in the transformers’ case. The temperature produced by this latter case is particularly interesting for

Table 9

Estimation of the cooling capacity using desiccant system.

	2009 Pole 1		2009 Pole 2		2014 Pole 1	
	Whole year		Whole year	When operated	Whole year	When operated
Cooling based on thyristor waste heat (kW)	77		53.6	77	— ^a	88.6
Cooling based on transformer waste heat (kW)	120		108	151.2	— ^a	146
Total cooling (kW)	197		163.6	228.2	— ^a	234.6

^a Temperature sensors failed in October.

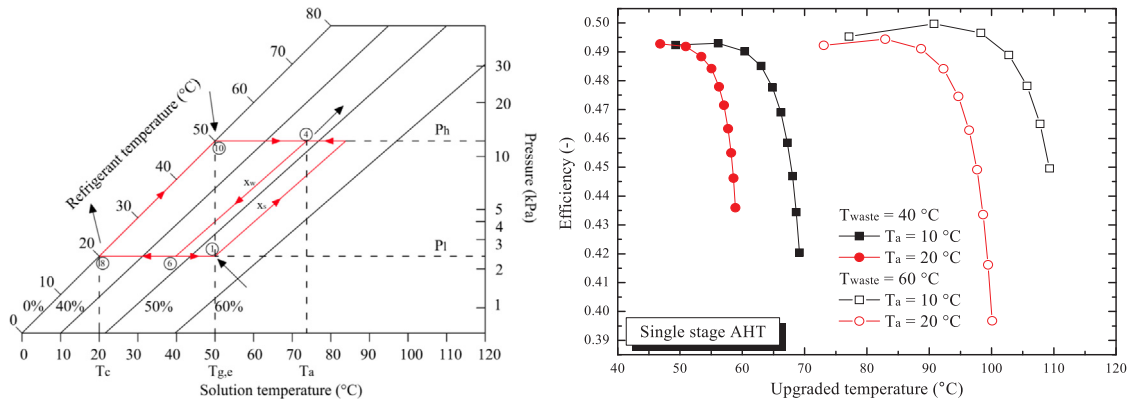


Fig. 14. P-T diagram of single effect absorption heat transformer (left) and achievable temperature lift (right).

combination with the ORC system.

Considering a 5% efficiency for a small-scale ORC [58], the conversion efficiency of the whole composed system for the recovery of a 40°C waste heat source and electricity production is 1.5%. Only about 18.35 kW electricity can be generated by this combined AHT + ORC system using the waste heat present in the year of 2009 with both poles operating. Table 10 summarises the estimated power producible by the system.

5. Retrofitting challenges

Once described the potential heat recovery strategies at Moyle interconnector and their performance, an evaluation of the best fluid employable as heat recovery and transfer medium (water or air) and of the possible retrofitting challenges on-site was performed.

5.1. Heat transfer medium

For both the heat recovery strategies, hot water can be used as due to low waste heat temperature ($< 100^\circ\text{C}$). The best retrofit strategy to obtain hot water from both thyristor cooling system and transformer cooling system is to install a liquid-to-liquid heat exchanger, e.g. a plate heat exchanger, at the upstream of an air-to-water heat exchanger in thyristor valves' cooling system and at the upstream of the oil-to-air radiator in transformer cooling system, respectively. The produced hot water can be pumped elsewhere to drive the desiccant evaporative cooling or the AHT + ORC system. Alternatively, the direct use of the hot air from the waste heat system is a viable alternative option to the use of hot water since the system naturally requires hot/warm air for the desiccant system. This solution avoids the cost for the plate heat exchanger because warm air is already available. For the liquid desiccant system, two heat recovery strategies can be performed with hot

air as illustrated by Fig. 16. The hot air produced by the air-to-water heat exchanger can be collected at either downstream or upstream of the fan.

The flexibility of liquid desiccant systems, namely their ability to indistinctly drive their regeneration cycle with hot air or water, widens the heat recovery feasibility with this technology for both retrofitting and new projects. The effect of the regeneration mode (air-heated or solution-heated) on the performance of the liquid desiccant air-conditioning system is reported by [59]. On the other hand, for solid desiccant systems, the situation is not as flexible as a liquid system since the regeneration and dehumidification occur in the same rotating wheel, therefore only collecting hot air downstream of the fan is possible for the solid desiccant system.

5.2. Thyristor valves' coolant heat recovery

The heat content of the hot air/hot water produced by the thyristor valve radiator may not be enough to drive the desiccant regeneration. Different solutions are used in desiccant systems, such as LiCl, LiBr, CaCl_2 , HCO_2K , each with a different thermodynamics behaviour, resulting in different regeneration temperature among them. Fig. 17 shows the desorption behaviour of different desiccant solutions on a psychrometric chart. The thermodynamic properties of desiccant solutions were obtained from [60–62].

The figure was obtained considering the equilibrium vapour pressure of four desiccant solutions with concentration typical for regeneration process, namely CaCl_2 solution (green line) 38% wt., HCO_2K (red line) 70% wt., LiCl (blue line) 38% wt., and LiBr (magenta line) 62% wt. and a regeneration efficiency of 0.7 [63]. The regeneration efficiency of a liquid desiccant system is defined as [64]:

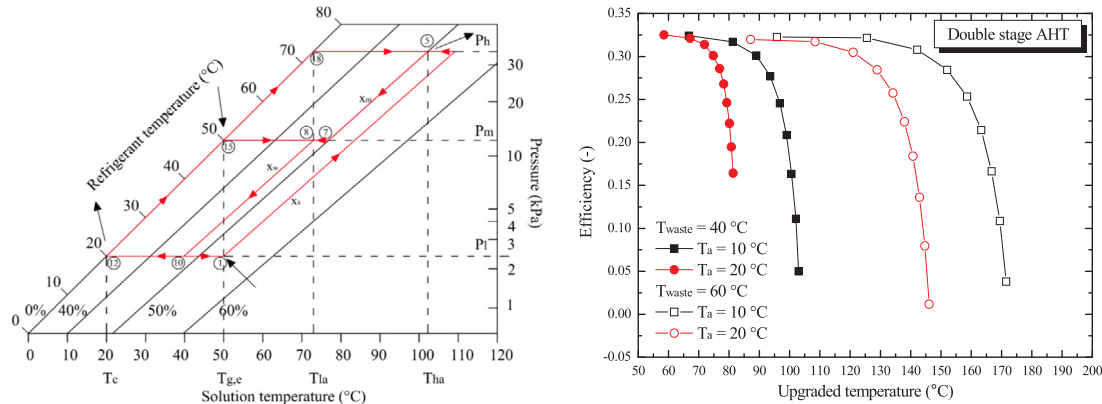


Fig. 15. P-T diagram of double effect absorption heat transformer (left) and achievable temperature lift (right).

Table 10
Power generation using the combined system of AHT and ORC.

	2009 Pole 1	2009 Pole 2		2014 Pole 1	
	Whole year	Whole year	When operated	Whole year	When operated
Power based on thyristor waste heat (kW)	5.78	4.02	5.8	–	6.65
Power based on transformer waste heat (kW)	4.5	4.05	5.67	–	5.48
Total power (kW)	10.28	8.07	11.47	–	12.13

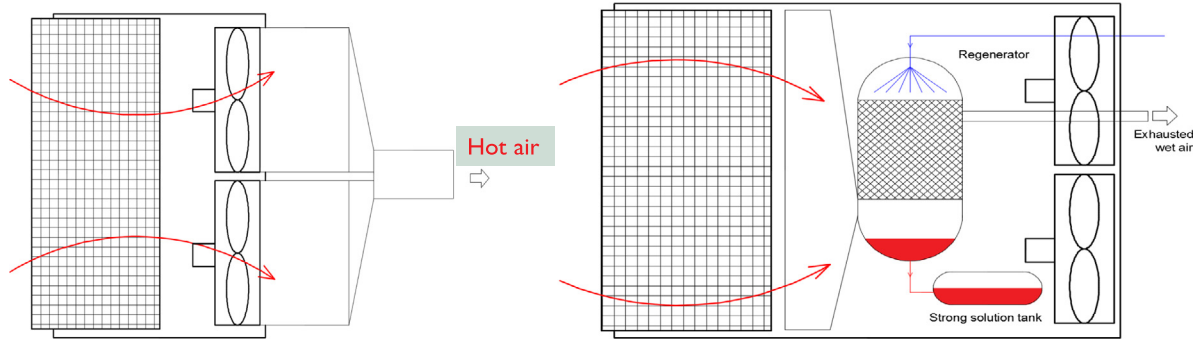


Fig. 16. Air as waste heat recovery medium, used at the downstream (left) and at the upstream of the fan (right).

$$\varepsilon_{\text{reg}} = \frac{\omega_{\text{air,out}} - \omega_{\text{air,in}}}{\omega_{\text{eq,sol}} - \omega_{\text{air,in}}} \quad (7)$$

where $\omega_{\text{air,out}}$ and $\omega_{\text{air,in}}$ represent the moisture content (kg dry air/kg H₂O) of the air outlet and inlet the regenerator shown in Fig. 11, while $\omega_{\text{eq,sol}}$ is the equilibrium moisture content of the desiccant solution entering the regenerator. The driving force of the moisture desorption (regeneration) process is the difference in the moisture content between the desiccant solution and the outdoor air, i.e. the higher the difference, the easier the regeneration process. Under the considered outdoor conditions, the figure shows how CaCl₂ is the only solution able to desorb its moisture content in the temperature range between 40 and 45 °C. HCO₂K and LiCl solutions present ability to desorb moisture but require a higher temperature for an efficient desorption process. LiBr solution cannot be regenerated with the thyristor valves' waste heat. Further experimental analysis must be conducted to prove the feasibility of CaCl₂ liquid desiccant system driven by thyristor valves' waste heat.

5.3. Transformer's coolant heat recovery

The higher temperature of the transformer's coolant oil (between 55 and 85 °C) is appropriate to drive the desiccant regeneration process. In HVDC converter stations, transformers are usually located next to the thyristor valves hall with the valves connected to the transformers through wall bushings [64]. Given the position of transformers and thyristor valve hall in the HVDC converter station, the identified heat recovery strategy is to utilise the transformer waste heat to dehumidify and cool the valve hall supply air with desiccant technology. The disposition of transformers and thyristor valves hall is depicted in Fig. 18.

6. Economic analysis

6.1. Heat recovery for electricity production

To evaluate the economic factors involved in the electricity production process, a literature review of the of AHT and ORC systems was performed. The economic analysis of AHTs was obtained considering the investment costs of comparable absorption chillers, considering the

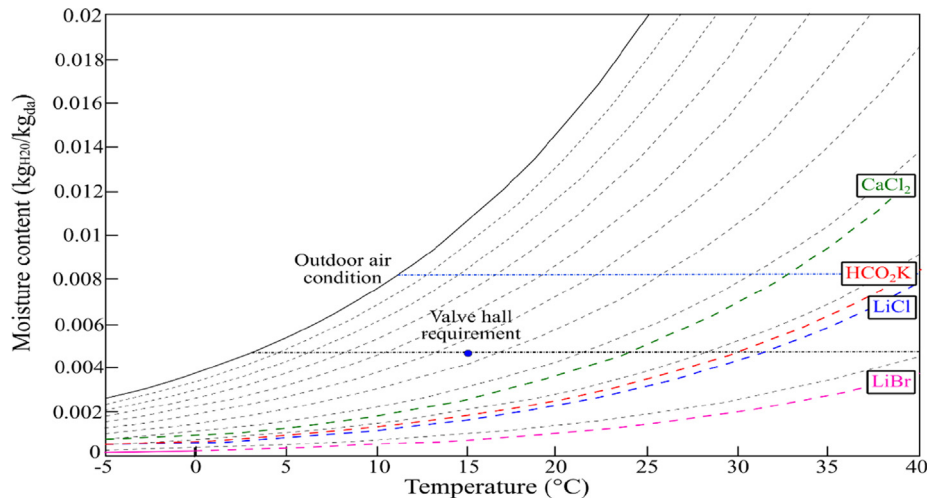


Fig. 17. Desorption ability of desiccant solution under Northern Ireland summer conditions.

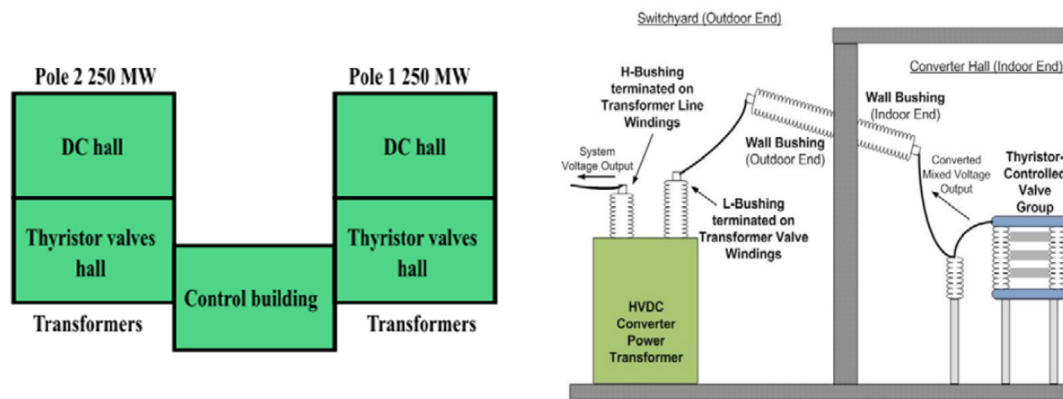


Fig. 18. Vertical (left) and lateral (right) view of transformer and thyristor valve hall of HVDC converter station, adapted from [33,65,66].

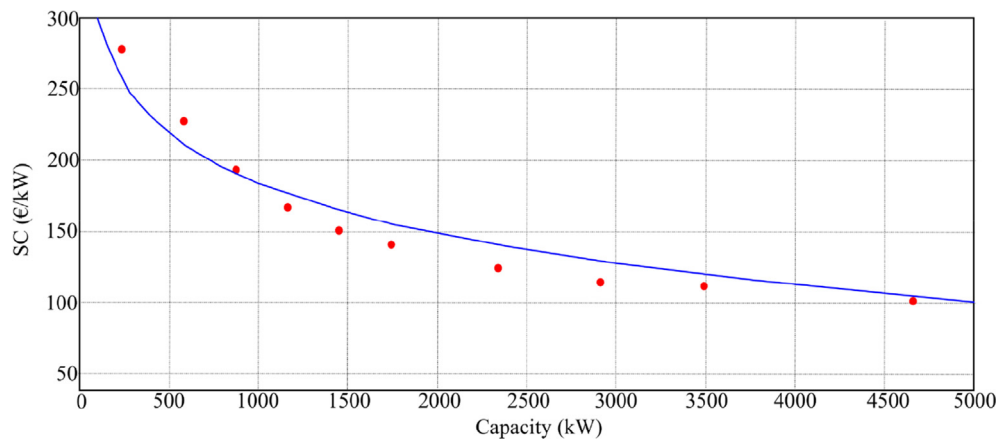


Fig. 19. Specific cost function depending on the cooling capacity of double effect absorption chiller.

lack of data on this new technology. A specific cost (SC) function for double effect AHT was regressed from [67]:

$$SC = -51.22 * \log(\text{Cooling capacity}) + 538.3 \quad (8)$$

Fig. 19 shows the specific cost function depending on the cooling capacity for double effect absorption chiller. Considering an efficiency of 30%, the capacity of AHT for waste heat from thyristor valves only is 196 kW and is 367 kW for waste heat produced from both thyristor valves and transformer. As calculated from the previous equation, the capital cost of a double effect absorption chiller would be 52,520 € (for thyristor valves heat recovery) and 86,550 € (thyristor valves and

transformers heat recovery).

Fig. 20 shows the specific cost function depending on the nominal output power of the ORC system [68]. As in the previous case, the literature review showed how lower size ORC systems present higher equipment cost. In the present study, a cost of 7 k€/kW was considered for a 9.8 kW ORC system, while 5.5 k€/kW is used for an 18.4 kW ORC system [68].

The results of the economic analysis of the heat upgrade and electricity production process at the Moyle interconnector are shown in Table 11. Some additional assumptions were used in the economic analysis:

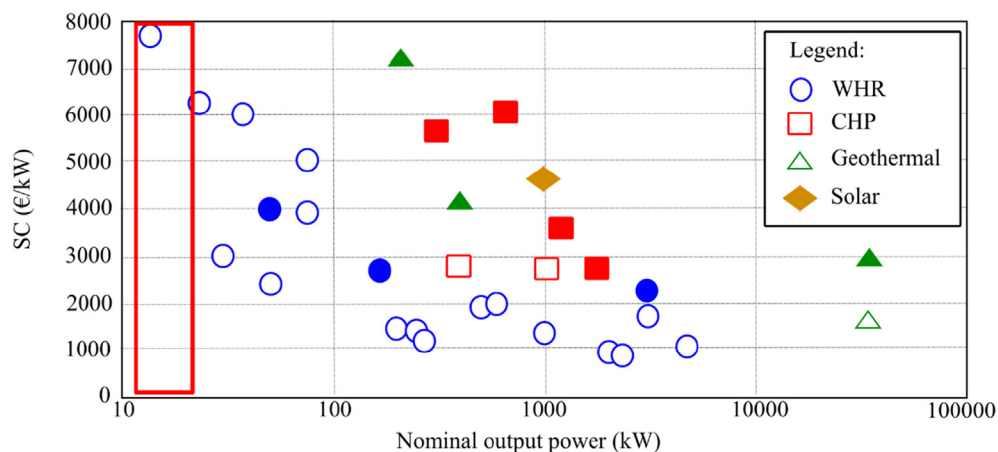


Fig. 20. Specific cost function depending on nominal output power of ORC system, . adapted from [68]

Table 11
Costs and payback period of AHT + ORC system.

	Case 1	Case 2
Waste heat (kW)	653	1223
Efficiency (%)	0.3	0.3
AHT power (kW)	196	367
ORC power (kW)	9.8	18.35
Earnings (€/year)	8548	16,074.6
AHT capital cost (€)	52,520	86,550
ORC capital cost (€)	68,600	101,200
Total capital cost (€)	121,120	187,750
AHT maintenance cost (€/year)	2626	4327.5
AHT electricity cost (€/year)	1489.2	3679.2
O&M ORC cost (€/year)	2575.44	4822.38
Total operation cost (€/year)	6690.64	12,829.08
Savings (€/year)	1857.36	3245.52
Payback period (year)	–	–

1. The setup costs are included in the capital cost of the combined system;
2. The yearly maintenance cost for the AHT is 5% of the capital cost of the system [69];
3. The operational cost for the AHT is obtained by the manufacturer manual [67];
4. The operation and maintenance (O&M) costs for ORC are 0.03 €/kWh [70];
5. The electricity cost is 0.1 €/kWh.

The table shows how the low electricity production (and related economic earning) together with the high capital cost does not produce remarkable economic savings for the studied combined heat recovery strategy, presenting not feasible payback period (higher than 50 years). The low-temperature waste heat and the current capital costs of AHT and ORC technologies limit the realisation of heat-to-electricity recovery technology at the Moyle interconnection station and in general in HVDC stations.

6.2. Heat recovery for dehumidification and cooling

6.2.1. Liquid desiccant capital cost evaluation

For the evaluation of the capital cost of a liquid desiccant system, a literature review was conducted [71–75]. One of the main problems for the evaluation of the capital cost of liquid desiccant systems is the lack of available data and the difference in the system configuration between the various references.

Being the liquid desiccant an open system technology which performance is highly dependent on the outdoor air condition, the characterisation of the cost function depending on the cooling effect is unreliable. A better strategy for the characterisation of the specific cost function of a liquid desiccant system is to evaluate its proportionality with respect to the air volume flow rate of the machine. A specific cost function depending on the volume flow rate was regressed to by the literature review. However, the cost function obtained for the liquid desiccant systems shows an unreliable behaviour for some cases. This difference is mainly due to the difference in the LD system cost between manufacturing cost, local distributor overhead costs, and end-users cost and on the typology of the liquid desiccant system employed (LDAC standalone system, internally-cooled system, etc.). For this reason and general consistency, a regression model for the specific cost function of the Kathabar liquid desiccant system was obtained and is shown in Fig. 21 [76]. The regressed specific cost function is:

$$SC = -7.9319 * (\text{Volume flow rate})^{(0.0877)} + 24.6067 \quad (9)$$

Considering as Ref. [36] for the ventilation air requirement of a thyristor valve hall of a 500 MW HVDC converter station, the Moyle's thyristor valves hall (250 MW each pole) requires 12,610 m³/h of

ventilation air. Using (9), the estimated capital cost of the required liquid desiccant system would be 81,350 €.

6.2.2. Results

An economic evaluation of economic savings achievable with liquid desiccant technology was performed. As in the previous case, some assumptions have been utilised for the economic analysis and are here summarised:

The setup costs are included in the capital cost of the desiccant cooling system;

The yearly maintenance cost of the combined liquid desiccant system is 2% of the capital cost [77], while the yearly maintenance cost of the vapour-compression electrical chiller is 3% of the capital cost [78];

The yearly operation cost of the desiccant system is 5% of the capital cost [77];

Temperature and humidity control in the valve hall is performed all the year-round to ensure proper operation of the thyristor valves;

The COP of the electrically-driven refrigerator is 3;

The electricity cost is 0.10 €/kWh.

Outdoor air condition data (temperature and relative humidity) of Larne, Northern Ireland (close to Ballycronan More), were collected on a three-hour basis in the period August 2017–July 2018 [79] and used in the analysis. The yearly outdoor air condition together with the valve hall's air requirement are displayed in Fig. 22.

The figure shows how the moisture content of outdoor air during the year is most of the times higher than the value required by the thyristor valves hall ($T = 15^\circ\text{C}$, $RH = 45\%$). For this reason, economic benefits are achievable with the proposed heat recovery strategy, able to efficiently control the moisture with the desiccant technology. During the colder months (November to April), the moisture content in the outdoor air is generally lower than thyristor valves hall requirement, i.e. little economic savings are possible. In the rest of the months (May to October), economic savings are achievable and are shown in Fig. 23. Possible additional sensible cooling (vapour compression or evaporative) may be needed in the hottest days of summer.

The calculated yearly savings in the considered period are 13,725.93 €. The results of the economic analysis showing payback period and LCOSE are presented in Table 12. The table shows how the payback period (8.7 years) and LCOSE (0.305 €/kWh) is high for the retrofit of the air-conditioning system of the thyristor valves hall, where two refrigerators (74 kW) are already installed.

However, in a new HVDC converter station employing liquid desiccant technology for the air conditioning system of thyristor valves hall much better economic performance would be achievable, under climatic conditions like those of Moyle. Given the ability of the technology in dealing with latent loads, the sensible cooling needed would be sensibly reduced. For this reason, in the design of a new HVDC converter station the size of the refrigeration system would be significantly reduced. Considering a new HVDC project two strategies were identified for the dehumidification and cooling:

- Combined liquid desiccant (LD) and vapour compression (VC) system. In Moyle, the liquid desiccant technology could be used to remove latent loads while one refrigerator (50 kW) is used as backup and to remove sensible loads during the hottest days of summer, instead of using 2*74 kW refrigerators. In this case, the savings in the capital cost for the vapour-compression cooling system would be about 29,400 €, considering a specific cost of 300 €/kW for the system [54]. For this new HVDC project, the economic performance of the heat recovery process increases, resulting in a payback period of 6.1 years and an LCOSE of 0.2 €/kWh. This solution would present both technologically and economic feasibility, considering the lifespan of the technology.

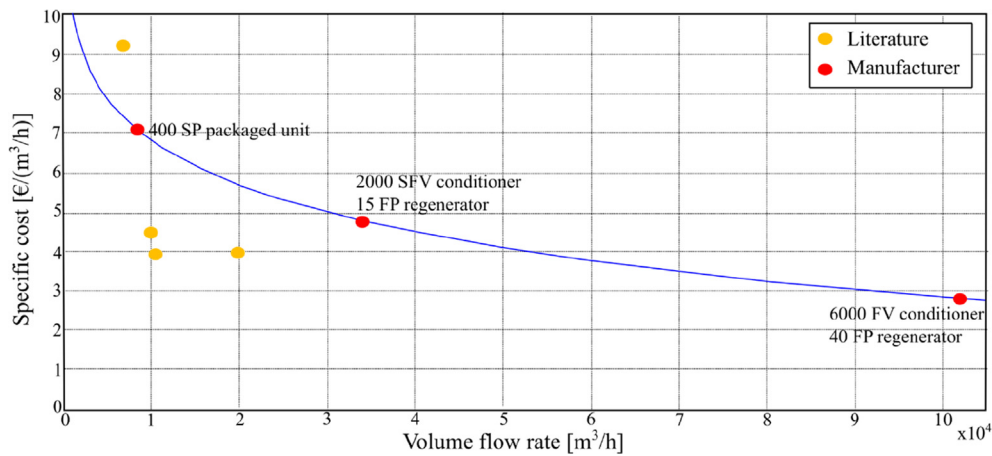


Fig. 21. Specific cost per air volume flow rate of Kathabar LD system.

- Combined liquid desiccant and direct evaporative cooling (DEC) system. In this case, the sensible heat removal would be performed by the direct evaporative system, resulting in higher economic savings respect the previous case. In this case, the savings in the capital cost for the vapour-compression cooling system would be about 44,400 €. The capital cost of a direct evaporative cooling system able to sensibly cool the thyristor valves hall would be 2470 € [80]. This heat recovery strategy results in being the most beneficial in terms of savings and environment, showing a payback period of 5 years and an LCOSE of 0.155 €/kWh. However, the technological feasibility of this combined system must be proved in hot and humid climates, given the sensible cooling removal ability of the technology and the importance of temperature and humidity control in HVDC stations.

The values obtained for the LCOSE are high, particularly for the retrofitting. As a comparison, a techno-economic analysis for geothermal heat recovery and cooling with absorption chiller technology [32] showed an LCOSE ranging between 0.1 and 0.16 €/kWh, depending on the climatic condition. Given the lifespan of the combined desiccant evaporative technology and its high electricity consumption reduction, this technology emerges as the most promising from an LCOSE analysis point of view.

One of the main advantages of the liquid desiccant technology

respect its competitor solid is the potential ability to dehumidify and cool, depending on the outdoor air conditions [38]. Considering the outdoor air conditions on the psychrometric chart shown in Fig. 22, the low temperature at Moyle interconnector causes sensible cooling to be only necessary on the hottest days of summer. As previously said, this operation can be performed by vapour compression or evaporative cooling system. The costs associated with sensible cooling would be very low for these combined technologies, given the low temperature and high humidity of the ambient air at the Moyle HVDC station, and the ability of the liquid desiccant technology to remove the latter.

7. Summary and conclusion

Technological and economic evaluation of the heat recovery of the low-grade waste heat sources present in the Moyle high-voltage direct current (HVDC) interconnector connecting Scotland and Northern Ireland was conducted. Given the worldwide increase of HVDC technology use for long-distance transport of electricity, the identification of heat recovery as a technologically and economically viable solution for HVDC interconnectors would result in significant environmental and economic benefits.

The data collection and quantification of the available heat at the Moyle interconnector station showed that: (1) 653 kW are available from the thyristor valves' cooling fluid at 43–45 °C, (2) 570 kW are from

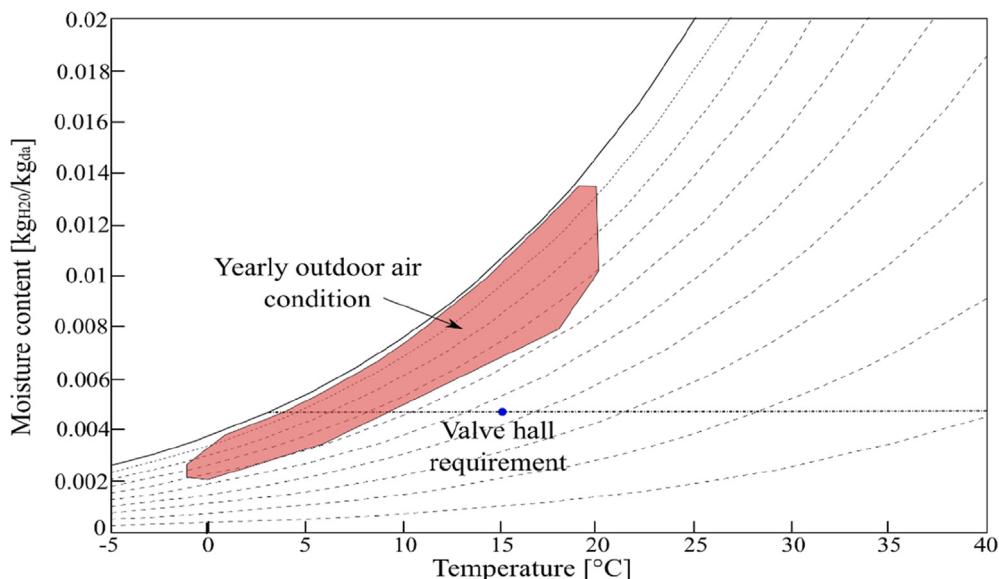


Fig. 22. Yearly outdoor air condition Larne, Northern Ireland.

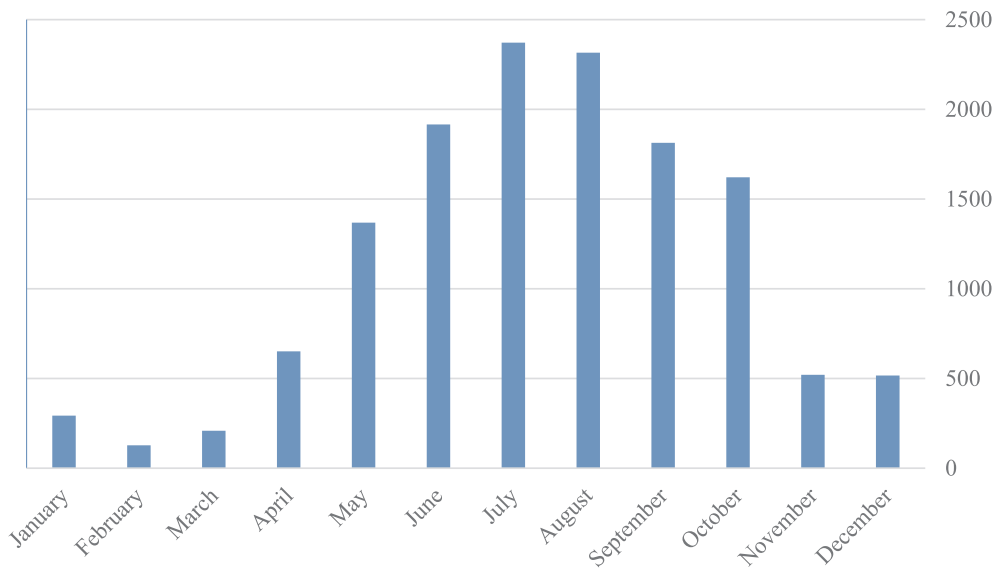


Fig. 23. Monthly economic savings (€) with liquid desiccant technology.

Table 12

Economic analysis of the heat recovery with desiccant system.

	Retrofit	New project 1	New project 2
Flow rate (m ³ /h)	12,610	12,610	12,610
LD capital cost (€)	81,350	81,350	81,350
DEC capital cost (€)	/	/	2470
VC capital cost savings (€)	/	29,400	44,400
Maintenance cost LD (€/year)	1627	1627	1676.4
Maintenance cost VC (€/year)	1332	432	/
Operation cost (€/year)	4067.45	4067.45	4191
Savings (€/year)	13,725.93	13,725.93	13,725.93
Payback period (years)	8.7	6.1	5
LCOSE (€/kWh)	0.305	0.2	0.155

the transformer's cooling fluid at 55–85 °C. Amongst evaluated heat recovery technologies for domestic or commercial local application, two heat recovery have been considered as interesting for HVDC interconnectors. The first one is the utilisation of the waste heat for dehumidification and cooling effect, with a combination of desiccant and cooling system (electric or evaporative). Alternatively, the possible production of electricity with Organic Rankine cycle (ORC) driven by low-temperature waste heat was evaluated. Absorption heat transformers are used to provide the heat required by ORC cycle. From the study, the following conclusions were obtained:

1. Production of electricity with Moyle HDVC interconnection station's waste heat is technologically but not economically feasible, given the current high capital cost and low efficiency of the systems.
2. Combined desiccant and evaporative cooling was considered the most promising technology. Given the importance of temperature and humidity control in the thyristor valves hall to ensure proper operation, economic savings are achievable with liquid desiccant technology, able to efficiently remove moisture and being driven by the waste heat sources present at the converter station.
3. The temperature of the low-grade waste heat is one of the main constraints influencing the efficiency and economic feasibility of the heat recovery project. The temperature of the heat recovered by the thyristor valves hall's cooling fluid may not be enough to drive the regeneration process of a desiccant system. Desiccant solutions characterised by a lower regeneration temperature, such as Calcium Chloride (CaCl₂), may be able to be regenerated by the heat content present. The transformer's cooling fluid heat recovery to drive liquid desiccant technology is considered a feasible strategy.

4. Retrofitting the Moyle converter station with liquid desiccant would present a high payback period (8.7 years) and levelised cost of saved energy (LCOSE) of 0.305 €/kWh. Better economic performances are obtained for a heat recovery project in a new design HVDC site. A combination of liquid desiccant and vapour compression cooling showed a payback period is 6.1 years and an LCOSE of 0.2 €/kWh. The best performing technological solution from an economic and environmental point of view is the combined desiccant and evaporative cooling system, presenting a payback period of 5 years and an LCOSE of 0.155 €/kWh. This value is comparable to other heat recovery projects.

The analysis has shown that the economic benefits resulting from the heat recovery process are strongly influenced by several parameters in HVDC interconnectors, such as system size, thyristor valves and transformers' cooling fluid temperature, outdoor air conditions (temperature and humidity), etc. Heat-to-dehumidification/cooling has been proved as the best heat recovery option for the Moyle interconnection station. Next steps of the research should evaluate the potential of combined desiccant and evaporative cooling in HVDC stations located in hot and humid climates where the humidity removal ability of the technology would result in higher economic savings.

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